Simultaneous radar and satellite data storm-scale assimilation using an ensemble Kalman filter approach for 24 May 2011

Thomas A. Jones[1], David Stensrud[2], Louis Wicker[2], Patrick Minnis[3], and Rabindra Palikonda[4]

1. Cooperative Institute for Mesoscale Meteorological Studies, University of Oklahoma, Norman, OK
2. NOAA/OAR/National Severe Storms Laboratory, Norman, OK
3. NASA Langley Research Center, Hampton, VA
4. Science Systems and Applications, Inc., Hampton, VA

1. Introduction

Assimilating high-resolution radar reflectivity and radial velocity into convection permitting numerical weather prediction (NWP) models has proven to be an important tool for improving forecast skill of convection. The use of satellite data for the application is less well understood only recently receiving significant attention. One important disadvantage of radar-data assimilation is that it does not capture the non-precipitation phase of cloud development during convective initiation. Since both radar and satellite data provide independent information, combing these two sources of data in a robust manner potentially represents the future of high-resolution data assimilation. This research combines GOES-13 cloud water path (CWP) retrievals with WSR-88D Doppler radar reflectivity and radial velocity to examine the impacts of assimilating each for a severe weather event occurring in Oklahoma on 24 May 2011. Data are assimilated into a 3-km model using an ensemble adjustment Kalman filter approach with 36 members over a two-hour assimilation window between 1800 – 2000 UTC.

2. Data and Methodology

a. Observations

Conventional observations, considered to be those most commonly assimilated into NWP models, include data from the Automated Surface Observing System (ASOS), Aircraft Communications Addressing and Reporting System (ACARS), radiosonde instruments, and Oklahoma Mesonet data.

The GOES imager takes multispectral images over the continental United States (CONUS) every 5 -15 min depending on the need (Menzel and Purdom 1994). Cloud properties are retrieved from 4-km GOES imager data for pixels classified as cloudy (Minnis 2008a, b) using the multispectral retrieval algorithm developed by Minnis et al. (2011) and adapted to geostationary data (Minnis et al. 2008a). Cloud properties retrieved include cloud top pressure (CTP), cloud top temperature (CTT), cloud emissivity, and cloud phase for high clouds having a cloud optical thickness (COT), and finally cloud water path (CWP), which represent the variable assimilated in these experiments.

WSR-88D Doppler radar reflectivity and radial velocity are obtained from 3 radars in central and western Oklahoma. Radar sites include Fredrick, OK (KFDR), Vance Air Force Base, OK (KVNX), and Twin Lakes, OK. Objectively analyzed radar reflectivity and radial velocity data are generated at 5-min intervals beginning at 1845 UTC and continuing until 2000 UTC.

b. Model design

Experiments are initiated from ensemble backgrounds generated from the Global Ensemble Forecast System (GEFS) analysis at 0000 UTC 24 May 2011. The GEFS is a 21-member ensemble version of the Global Forecast System (GFS) run operationally by NCEP. For this event, GEFS has a 1-degree grid spacing with 27 vertical levels from the surface to 10 hPa. Initial and boundary conditions at 15 km (mesoscale) are generated from the original GEFS members. Simultaneously, a 3 km (storm-scale) grid is downscaled from the mesoscale grid using a 1-way nested grid configuration with information only exchanged at the lateral boundaries at the time the storm-scale grid is generated.

The 3-km storm-scale ensembles at 1800 UTC generated using the method described above are used as initial conditions for a smaller (170 x 170) 3-km domain to test satellite and radar data assimilation. The smaller domain is centered in west-central OK and covers the western two-thirds of the state while also reaching into north TX and southern KS. Data are assimilated beginning at 1800 UTC and continuing at 15-min intervals to 1845 UTC, at which time, convection initiates in western OK. Following 1845 UTC the assimilation frequency increases to 5 min and continues out to 2000 UTC. Thereafter, two sets of forecasts are generated for each member beginning at 1930 and 2000 UTC and continuing for 90 min with output generated at 5-min intervals. Only the former is shown here.

Using this process, five experiments are defined each assimilating different combinations of conventional, satellite, and radar data. The control (CNTL) experiment only assimilates conventional observations during the assimilation experiments and represents a baseline on model performance without the aid of high resolution remote sensing data assimilation. The PATH experiment assimilates both conventional observations and satellite CWP retrievals when available. Two separate radar data assimilation experiments are performed. One assimilates radial velocity and positive (> 0 dBZ) radar reflectivity (RADP) and the other assimilates radial velocity, positive reflectivity, and clear-air (0 dBZ) reflectivity (RAD0). The final experiment (PATHRAD) combines conventional, satellite, and radar data to determine whether the combination of all data sets provides skill over either radar or satellite data alone

3. Results

The positive impacts of assimilating both satellite and radar data can be seen at several points during the assimilation cycle when comparing ensemble mean analyses with corresponding satellite and radar observations. Convection initiates in all experiments except CNTL between 1910 and 1915 UTC and rapidly increases in coverage and intensity thereafter. The corresponding 1915 UTC observed (a.) and simulated reflectivity at 4 km for each experiment (b-f.) are shown in Fig. 1. The CNTL experiment fails to generate any simulated reflectivity at these locations (Fig. 1b), while having a large area of 5-10 dBZ further east. The PATH experiment eliminates this feature while generating weak reflectivity near the locations of the northern two cells, with a single spurious maximum biased slightly eastward (Fig. 1c). The RADP experiment is stronger with the simulated reflectivity, as expected, while retaining the faults of CNTL (Fig. 1d). RAD0 (Fig. 1e) is similar to RADP except that it corrects the reflectivity bias to the east. Despite assimilating reflectivity for ~30 min, the radar only experiment still fail to correctly capture the developing storms. When no positive reflectivity exists in the model, high reflectivity observations associated with developing convection are considered outliers and may not be assimilated. This slows down the spin-up of convection within the model compared to observations. The PATHRAD experiment generates > 50 dBZ reflectivity cores associated with the northern two cells with a weaker, but correctly located reflectivity core corresponding to the southernmost cell (Fig. 1f). The faster increase in convection in PATHRAD is a result of the satellite and radar data providing a signal to the model that convection is present. For this case, the satellite data help generate high-CWP clouds and their associated cloud hydrometeors, which then allows the radar data to build upon those already present hydrometeors instead of having to do it alone, also indicating that fewer reflectivity observations are being considered outliers. Thus, the combination of satellite and radar data provides a clear benefit at this early period of the assimilation cycle.

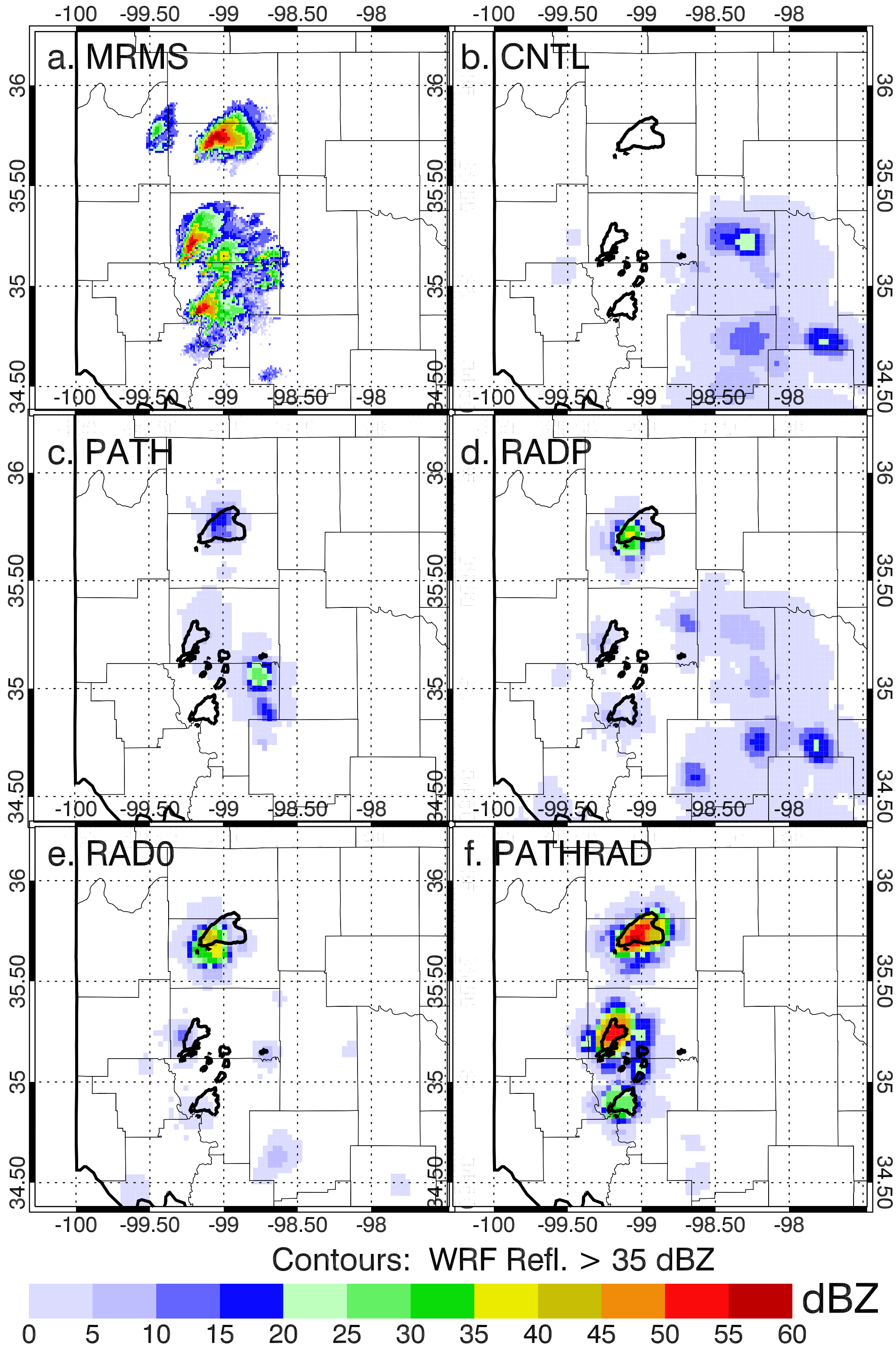

Figure 1. WSR-88D radar reflectivity at 4 km (a) and ensemble mean simulated reflectivity from CNTL (b), PATH (c), RADP (d), RAD0 (e), and PATHRAD (f) experiments analyzed at 1915 UTC. Black contour on b-f indicates where WSR-88D radar reflectivity is > 35 dBZ.

The true test of assimilating both satellite and radar data is to measure the forecast impact relative to only assimilating each of these data sets separately. 90-min forecasts are initiated at 1930 UTC and 2000 UTC. By 1930 UTC, the experiments have been cycling at 5-min intervals for 45 min and reach the stage where each has spun-up deep convection. Initiating the forecast at this time allows for the study of the importance in spin up characteristics from assimilating both radar and satellite data translates into the forecast evolution convection. To assess the impact of assimilating both satellite and radar data throughout the entire 90-min period, the probability of reflectivity > 45 dBZ between 1930 – 2100 UTC is calculated for PATH, RADP, RAD0, and PATHRAD and compared against the track of observed 45-dBZ reflectivity over the same time period (Fig. 2). The probability is calculated by determining the number of ensemble members that generated reflectivity > 45 dBZ at a given location at a specific time. Then, the maximum probability at that location over all forecast times is taken used to generate the plots. PATH generates >80% probabilities associated with the convection present in the southern portion of the domain while being too fast with high probabilities extending well eastward of the end of the observed 45-dBZ path (Fig. 2a). All the satellite and radar data assimilating experiments have an eastward bias in the forecast reflectivity compared to observations. An analysis of the synoptic conditions found that the 500 – 200 hPa wind speeds in the model analysis are ~5 m s-1 too high compared to radiosonde observations. The wind speed bias results in faster storm motion in the model leading to the location bias observed in the forecast.

The northern storms are also poorly captured, but recall that PATH had difficultly in generating high reflectivity cores, even though it did show evidence of development. Both RADP and RAD0 generated probabilities near 100% initially with some storm tracks being captured all the way out to 2100 UTC (Fig. 2b, c). Interestingly, RADP has difficulty retaining the northern storm compared to RAD0, while RAD0 has slightly lower probabilities associated with the southern supercell from 1930 UTC. PATHRAD is generally similar in nature to RAD0, but has several key differences. First, the higher probabilities exist for a longer period of time with the storm beginning near 36.0°N and 99.0°W (Fig. 2d). The probabilities for the southern complex are similar, but PATHRAD does not have a 70% tongue extending out too far northeast as present in RAD0. Finally, PATHRAD generates higher probabilities with developing convection in far southern OK than either of the radar-only experiments. From an objective standpoint, the PATHRAD experiment is generally superior though the improvement is small compared to either RADP or RAD0.

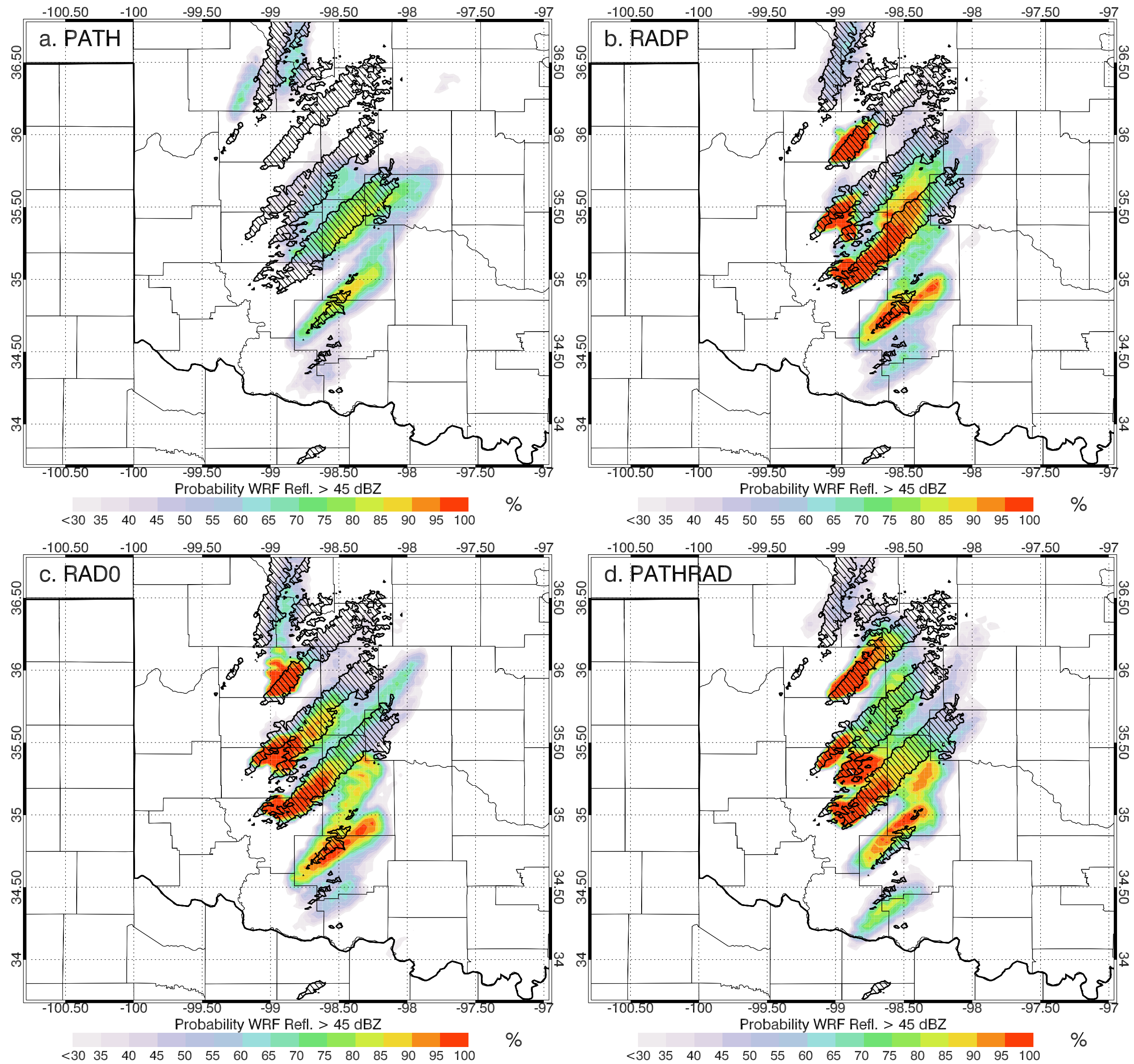

Figure 2. Probability of simulated 4-km reflectivity from each experiment > 45 dBZ for the 90 min forecast period between 1930 and 2100 UTC. Hatched area indicates the region of observed WSR-88D radar reflectivity > 45 dBZ.

4. Conclusions

Assimilating both high resolution satellite and radar data into a convection permitting model using an EaKF approach has proven viable despite the many challenges required to be overcome to allow satellite and radar data to work together and not against each other. The advantages of assimilating both types are evident in several comparisons of analyses and forecasts against corresponding observations. High-resolution satellite retrievals of cloud properties are able to successfully initiate and maintain convection when assimilated into a convection-permitting model. Given the 2-D nature of the observations, the resulting storm-structure is rather ambiguous and smoothed out, but assimilating satellite data provided significantly improved forecast skill over those forecasts generated from no assimilation of any high resolution data set. In situations where resources are limited, assimilating satellite data may represent a viable alternative to radar data. Assimilating CWP also generally outperformed assimilating clear-air reflectivity, even when not considering resource requirements. The experiment that assimilated clear-air reflectivity, RAD0, consistently under-analyzed and under-forecast atmospheric CWP content compared to observations. Clear-air reflectivity does have the desired impact of reducing spurious convection early in the assimilation cycle, but again CWP generally does better while having a much smaller set of observations. Assimilating clear-air reflectivity actually reduced reflectivity forecast skill out to 30 minutes relative to assimilating positive reflectivity observations alone. Therefore at least for this case, it was faster and more accurate to assimilate CWP away from convective cores rather than assimilating clear-air reflectivity.

The impacts of assimilating CWP in combination with radar data appear to be greatest early in the analysis period when suppressing spurious convection and capturing convective initiation. The positive impacts of assimilating CWP appear to decrease somewhat as convection matures and retrievals become saturated. Still, assimilating CWP continues to improve the analysis and forecast of anvil-like features in the model and remaining convection-free regions within the model domain.